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Characterisation of collapsing loess by seismic dilatometer

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ABSTRACT

Structural collapse and sudden volume changes represent a major geotechnical issue, particularly in loess soils. There are different criteria for assessing collapse potential based on laboratory test results, which require the collection of undisturbed samples from test pits. This can be a complicated and costly procedure, often financially unjustified for smaller projects. This paper presents the results of seismic dilatometer tests (SDMT) performed at a single location in a loess soil in Belgrade, in addition to the results of single oedometer collapse tests performed on high quality samples from test pits.

After comparing laboratory test results it was possible to determine that in samples collected from boreholes, dry unit weight is approximately 20% higher than in block samples taken from test pits, while moisture content is between 1 and 4% higher. Unit weight estimated from DMT is on average 15% higher than the unit weight obtained from block samples.

The constrained modulus (M_{DMT}) determined by DMT are highly compatible with oedometer modulus (E_{oed}) obtained from samples at natural moisture content. This paper presents two possible ways of identifying collapsing loess based on intermediate DMT parameters and the ratio of G_0/M_{DMT}. The tests results indicate that if the ratio between the material index (I_D) and the horizontal stress index (K_D) is greater than 5, the danger of collapse is imminent. Simultaneous observation of the changes of I_D and K_D with depth on a semi-log graph in the same scale is recommended. In this way the relative distance between them may be clearly noticed; the larger the distance becomes, the greater the risk of collapse. In the collapsing loess ratio G_0/M_{DMT} is found to be higher than 21 for K_D less than 0.6, while in non-collapsing loess G_0/M_{DMT} is less than 21 for higher values of K_D. In terms of DMT, loess is considered as underconsolidated soil, which is one of the most common “definitions” of loess.

1. Introduction

Collapsible soils are underconsolidated soils in which consolidation is delayed until the combined influences of load and moisture content allow particle slipping and rearrangement, usually after bonds become weakened by wetting, but also on occasion from application of load alone (Handy and Ferguson, 1994). The particularity of the construction of engineering objects on loess soils is reflected in the need to detect areas that are susceptible to large volume changes after wetting, and to quantify the expected volume change. There are different criteria for identifying collapsing zones (for an overview see Lutenegger and Saber, 1988; Rogers et al., 1994). Most of these criteria are based on the measurement of dry unit weights or consistency limits.

Gibbs and Holland (1960) suggest that the dry unit weight is the primary feature that governs susceptibility to settlement and that if the dry unit weight is less than 12.6 kN/m^3 loess is considered highly prone to settlement by wetting. The critical ranges of density values are governed by the type of soil which is indicated by the liquid limit. Recently, Yuan and Wang (2009) showed that sand and clay content are among the major factors that control loess collapsibility. The direct quantification of volume change that occurs when soil undergoes collapse is usually obtained by conducting oedometer tests on undisturbed specimens (Lutenegger and Saber, 1988). A measure of the tendency to such deformation can be assessed by Eq. (1):

$$I_c = \Delta e/(1 + e_1) \quad (1)$$

where I_c is collapse potential, Δe is the change in void ratio resulting from wetting and e_1 is the void ratio before wetting. Generally, values of I_c greater than 0.02 are indicative of soils considered dangerous with respect to collapse (Lutenegger and Donchev, 1983; Rogers et al., 1994). NAVFAC (1986) defines the degree of collapse based on collapse potential (CP), which is defined in the same way as I_c but at the stress level of 200 kPa using the initial void ratio instead of the void ratio before wetting. The susceptibility of loess to subsequent settlement due to increased wetting depends on the stress level, initial dry unit weight and its natural moisture content (Milovic, 1988).

In the last decade seismic dilatometer (SDMT) has been extensively used as in situ tool for the site characterisation (see e.g. Cavallaro et al.,

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2006a, 2006b, 2012; Viana da Fonseca et al., 2006, 2010; Simonini et al., 2007; Monaco et al., 2011, 2014; Cruz et al., 2012). On the other hand, the results of flat dilatometer tests (DMT) conducted in loess are rather limited in number and are generally based on the capability of DMT to indicate potential collapse zones and the overconsolidation ratio (Lutenegger and Donchev, 1983; Hamamdshiev and Lutenegger, 1985; Handy and Ferguson, 1994; Handy, 1995; Devincenzi and Canicio, 2001). No SDMT results obtained in loess have been presented so far.

2. Scope of research

Loess is a specific material from which it is particularly difficult to obtain undisturbed samples by conventional drilling methods. Handy (1995) reported very low sample recovery (67%) due to compression in collapsing loess. Milovic (1988) highlighted several important issues concerning the impact of mechanical disturbance on soil.

Some of the fundamental conclusions imply that the higher the porosity of loess, the greater its susceptibility to mechanical disturbance, and also that serious errors are possible if (for determining the basic parameters) samples are taken with a thin walled sampler. The alternative method is to take samples from test pits, which is usually complicated and not economically viable. Accordingly, the solution may be found in the in situ tests such as CPT and DMT, which could be used in order to identify potential collapse zones or potential sampling locations, or to attempt to directly obtain the value of the constrained modulus (M_{DMT}) for settlement prediction.

Furthermore, in terms of deformability, loess is anisotropic, that is, different modules may be expected in horizontal and vertical directions (Milovic, 1988). Some results indicate that loess can be isotropic with regard to strength parameters (Parsons et al., 2009). This can be related directly to in-situ tests, such as DMT, which are performed in a horizontal direction.

The primary purpose of this research is to:

- Demonstrate that it is possible to isolate collapsing loess zones by means of intermediate DMT parameters;
- To determine G_0/q_c ratios for loess and compare them to other structured soils;
- To extend G_0/M_{DMT}-K_D diagrams for low values of horizontal stress index K_D;
- Compare the value of M_{DMT} obtained from DMT, according to correlations given by Marchetti (1980), and the oedometer modulus E_{oed}, determined from block samples with natural moisture content. The emphasis is on the first collapsing loess horizon.

3. Seismic dilatometer

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT) with a seismic module placed above the DMT blade. The seismic module is used for obtaining the vertical profile of shear wave velocity V_s. From V_s the maximum shear modulus G_0 may be determined using the theory of elasticity. The test procedure consists of pushing a 94 mm wide, 14 mm thick steel plate with an approximate 16° cutting edge into the soil and then expanding a 60-mm diameter thin metal membrane, mounted flush on one side of the plate, horizontally against the soil by means of gas pressure. The test operator obtains two pressure readings in approximately 1 min: the A-pressure is required to just begin to move the membrane into the soil and the B-pressure is required to move its centre 1.1 mm into the soil. These two pressures, when corrected for membrane stiffness, provide data relating to the in situ horizontal stress and soil modulus at the test depth. The operator then proceeds to the next test depth, usually 20 cm deeper, and repeats this procedure. Detailed description of the DMT equipment and test procedure can be found in Marchetti (1980) and Marchetti et al. (2001). Measurements of V_s are usually obtained every 0.5 m. Obtaining common soil parameters from corrected pressure readings is not a direct procedure, but includes an additional step of identifying three intermediate DMT parameters, of which two are independent (Marchetti et al., 2001):

$$\text{Material index}, I_D = (p_1 - p_0)/(p_0 - u_0) \tag{2}$$

$$\text{Horizontal stress index}, K_D = (p_0 - u_0)/\sigma'_{v0} \tag{3}$$

$$\text{Dilatometer modulus}, E_D = 34.7(p_1 - p_0) \tag{4}$$

where: u_0 is preinsertion in situ equilibrium pore pressure and σ'_{v0} is preinsertion in situ vertical effective stress. Key DMT design parameters are I_D (material index) and K_D (Robertson, 2009). Both parameters are normalized and dimensionless. I_D is the difference between the corrected lift-off pressure (p_0) and corrected deflection pressure (p_1) normalized by the effective lift-off pressure ($p_0 - u_0$). K_D is the effective lift-off pressure normalized by the in situ vertical effective stress. The dilatometer modulus E_D can also be expressed as a combination of I_D and K_D in the form (Robertson, 2009):

$$E_D/\sigma'_{v0} = 34.7 I_D K_D. \tag{5}$$

According to Marchetti (1980), the soil type can be identified as follows:

$$\text{clay} \quad 0.1 < I_D < 0.6 \tag{6}$$

$$\text{silt} \quad 0.6 < I_D < 1.8 \tag{7}$$

$$\text{sands} \quad I_D > 1.8. \tag{8}$$

Marchetti (1980) suggested that I_D is a parameter reflecting the mechanical behaviour of the soil rather than the results of the sieve analysis.

K_D provides the basis for several soil parameter correlations. In general, K_D reflects the cumulative effect of factors such as relative density (in sands), in situ K_0, prestressing, ageing, cementation, etc. and does not permit identification of the responsibility of each factor (Marchetti, 1982). In genuine NC clays (no ageing, structure, cementation) the value of K_D is $K_{D,NC} \approx 2$. The K_D profile is similar in shape to the OCR profile, hence helpful for understanding the soil deposit and its stress history (Marchetti, 1980). Marchetti (1982) found in loose sands ($I_D > 1.8$) values of K_D as low as 0.6. Lutenegger and Donchev (1983) reported even lower values of $K_D = 0.3$ in unweathered collapsing loess in which $I_D > 1.8$ was found.

In this paper, the only common soil parameter that will be considered is the constrained modulus M_{DMT}, and consequently, the background for this parameter is also introduced. M_{DMT} is the vertical drained one-dimensional tangent modulus at σ'_{v0} and is the same modulus which, when obtained by oedometer is called E_{oed} (Marchetti et al., 2001). M_{DMT} is obtained by applying correction factor R_M to E_D according to the following expression:

$$M_{DMT} = R_M E_D. \tag{9}$$

R_M is a function of K_D and I_D, but K_D has a major influence on M_{DMT}. According to Marchetti (1980), R_M increases with K_D. If R_M is less than 0.85 it should be set to 0.85, meaning that 85% of calculated E_D is used as M_{DMT} value. The necessity of applying the correction R_M to E_D, and its derivation, can be found in Marchetti et al. (2001) and Marchetti (2011). One of the reasons is that the direction of loading is horizontal while M_{DMT} is vertical, which can have significant influence in loess, based on the conclusion of Milovic (1988), as stated in Section 2.

4. Site description

The exploration area includes part of the "Zemun loess plateau", which covers a large area of Belgrade. During the 1970s and 1980s, in the course of intensive development and construction in Belgrade, considerable experience and knowledge were accumulated with respect to loess as a foundation soil.

Over the past few years, adverse phenomena such as collapse and slope instability have occurred on several occasions, thus endangering buildings and transport infrastructure. At the site, it is possible to distinguish three different loess horizons separated by buried soil. The first loess horizon has a preserved primary macroporous structure. The second and the third loess horizons have changed under the influence of wetting and overburden weight. Compared to loess, the buried soil has a characteristically high fraction of clay. Geologically, this loess is normally consolidated.

Fig. 1 presents the layout of in situ tests with the soil profile and photographs of samples obtained from borehole BH-1. Three boreholes were drilled in order to conduct standard penetration tests (SPT) and to install the piezometers. SPT were performed at approximately every 2 m. Two mechanical CPT and three DMT were carried out, of which two DMT were with V_s measurements. V_s measurements were made at every 0.6 m. Two 3.0 m deep test pits were excavated to collect block samples. A photograph of test pit TP-1 is given in Fig. 1. The approximate dimensions of the block samples were 30 × 30 × 30 cm.

5. Laboratory testing

All laboratory tests were made on samples taken from the first loess horizon. According to USCS it can be classified as low plasticity clay (CL). Calcite content for all samples tested ranged between 7.8 and 20.3%. The results of grain-size analysis are shown in Fig. 2, along with the gradation curves established by Gibbs and Holland (1960). Fig. 2 shows that the first loess horizon falls into a clayey loess area, according to the limits given by Gibbs and Holland (1960). It appears that clay minerals are a major cementing material, which is evident from the oedometer test results since sudden settlements occur after the addition of water, which should not happen if the cementing material is carbonate (Gibbs and Holland, 1960). Dry unit weight and moisture content were determined on samples taken from pits and piezometer boreholes for comparison purposes, and the results are shown in Fig. 3. Two samples from boreholes BH-1 and BH-2 were tested separately in two laboratories. Fig. 3 clearly shows that the dry weight of samples taken from the boreholes is approximately 20% higher than the dry weight of samples taken from the test pits. Also, the natural moisture content obtained from the block samples is on average between 1 and 4% lower than the values obtained in the samples from boreholes. This implies that the loess porous structure is significantly compressed during the sampling process. It would be a serious error to apply some of the criteria for collapsibility assessment based on γ_d and consistency limits based on

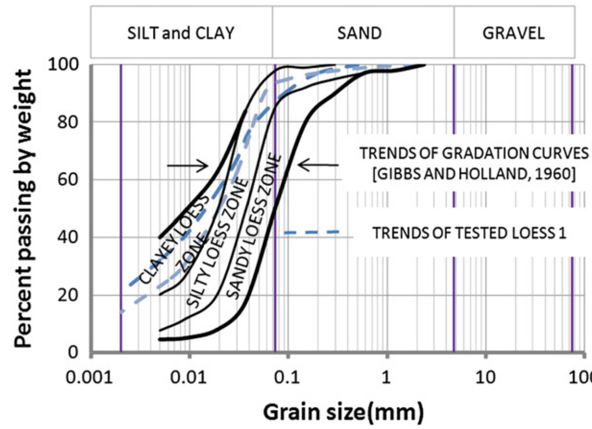

Fig. 2. Trends of gradation curves.

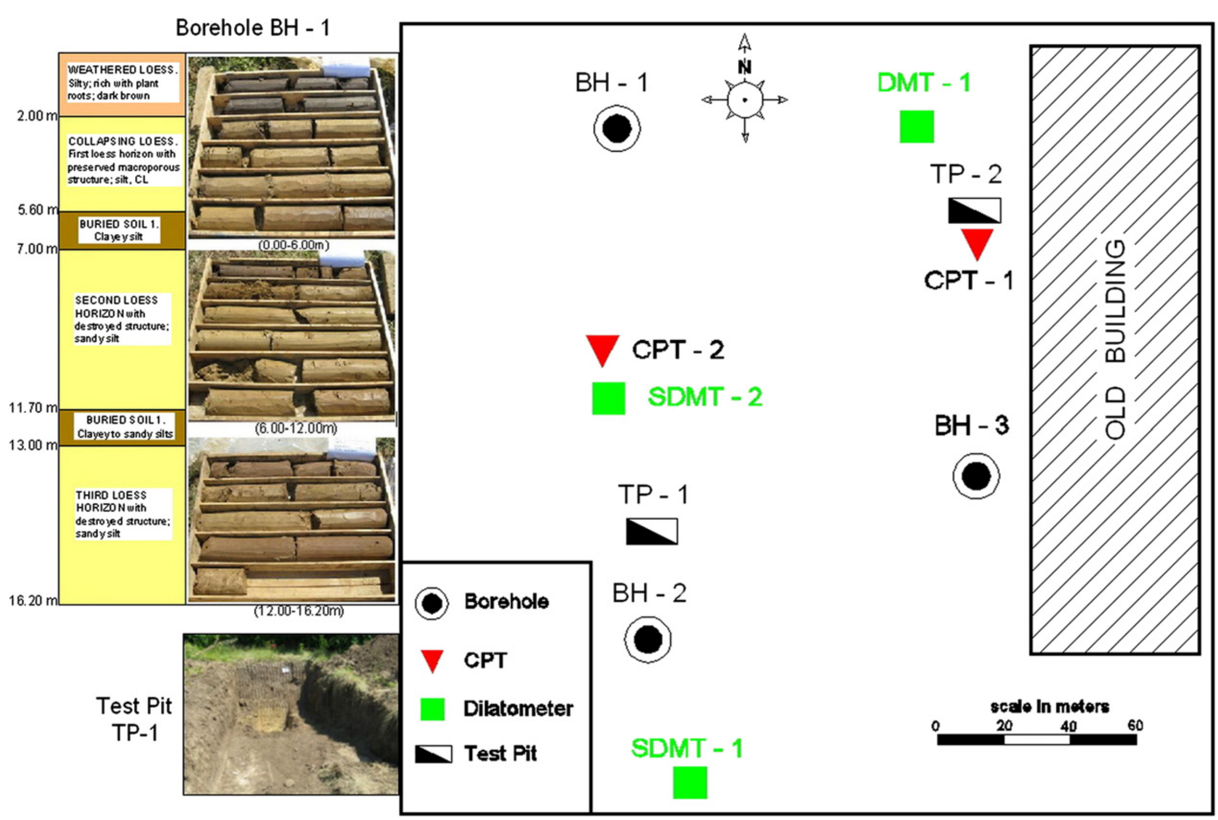

Fig. 1. Layout of in situ tests with soil profile and photos of the samples obtained from borehole (BH-1).

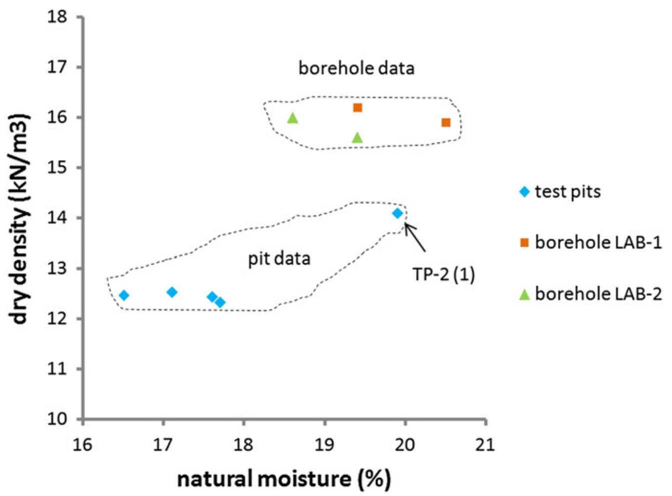

Fig. 3. Sensitivity of moisture content and dry unit weight on mode of sampling.

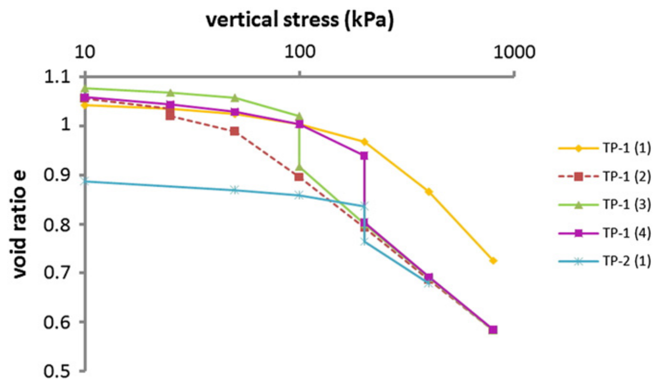

Fig. 4. Single oedometer test results.

borehole data alone. The sample taken from pit TP-2 has higher values of γ_d and moisture content, but this may be due to its position, which is located immediately next to an old building. In this area, loess is probably weathered and compacted under the influence of construction works and frequent wetting from surface water drainage that carries rainwater and runs along the building. This becomes even more obvious after analysing the values of q_c (CPT-1), which range from 2 to 3 MPa, as opposed to the values of q_c (CPT-2) in unweathered loess, which range between 1 and 1.5 MPa. DMT-1 did not detect this phenomenon, which is probably due to its distance from the building.

Three single oedometer tests were performed on samples taken from pit TP-1 whereas the water was added at the following stress levels: 25 kPa, 100 kPa and 200 kPa. One sample was tested at the natural moisture content. One oedometer test was also performed on a sample taken from pit TP-2 with the stress level of 200 kPa prior to wetting. Specimen dimension diameter/height ratio was approximately 10.2 cm/3.2 cm. In this way, at least to some extent, scale effects were taken into account, which could be expected to be significant in loess containing macropores. Oedometer test results are shown in Table 1 and Fig. 4. Single oedometer test results show an increasing *CP* with increasing stress level prior to saturation. For the stress level prior to saturation of 200 kPa, *CP* is 6.6% for samples taken from TP-1, which indicate trouble based on the description of the severity of the problem according to NAVFAC (1986). The sample saturated at 25 kPa shows a small sudden change in volume immediately after saturation, however, as the vertical stress increases settlements become more pronounced than in samples tested at natural moisture content. It should be noted that, after saturation, all the curves fall on the curve of the sample saturated at 25 kPa and that when the sample is saturated, constrained modulus increases linearly with increasing vertical stress. This is also typical for a sample taken from TP-2, which shows a lower degree of collapse due to higher density. The same post-saturation curve implies that bonding completely breaks down immediately on wetting and that a lower ultimate void ratio is reached at the specific stress level after saturation.

6. Field investigations

Vertical profiles of SDMT (DMT), CPT and SPT are shown in Figs. 5 and 6. Fig. 5 shows the vertical profiles of I_D, K_D, M_{DMT} for DMT-1, cone resistance (q_c) of the adjoining CPT-1 test and SPT N values obtained in boreholes BH-2 and BH-3. I_D and K_D are given on a semi-log graph in the same scale for easier comparison of results. Fig. 6 shows the same parameters but for SDMT-2 and CPT-2, along with V_s from SDMT-2 and SDMT-1. SDMT-1 test results are not shown, but they are very similar to DMT-1. Throughout testing, piezometric measurements were performed and the level of water was at 10 m. From Figs. 5 and 6 it can be seen that in the first loess horizon the number of blows of the SPT increases with depth almost linearly from $N = 3$–5 at 2 m to $N = 10$–12 at 6 m. A similar trend is observed for M_{DMT}. On the other hand, q_c decreases with depth. Detailed comparison of SPT results with other field tests is not considered in this paper. SPT results are shown as a reference for the purpose of comparison with loess soils in other regions of the world.

It should be noted that false energizations due to vibrations of the penetrometer were detected at depths of up to 8 m, which may indicate a significant "dynamic" sensitivity of loess. For this reason, the penetrometer had to be shut down while performing seismic tests. As the main emphasis is on the seismic dilatometer, in subsequent paragraphs identification of collapsing loess based on: a) intermediate DMT parameters and b) seismic measurements will be discussed.

7. Identification of collapse by intermediate DMT parameters

Figs. 5 and 6 indicate high K_D values in the first two metres, which can be attributed to weathering. From borehole logs and pits it was found that in this near-surface zone loess is rich with plant roots and clay minerals, probably expansive, which could explain high K_D values. Values of I_D indicate a silty sand region and they are lower than values of K_D. The weathered zone is less marked from CPT q_c values. The first two metres are regarded as non-collapsing.

Under this zone at approximately two metre K_D, after intersecting I_D, starts to rapidly decrease, contrary to I_D which increases rapidly. Here in the first loess horizon, extremely low values of K_D, lower than 0.6, are found, especially in the SDMT-2 profile where K_D decreases to 0.2.

Table 1
Single oedometer test results.

Pit no.	Sample no.	Initial void ratio e_0	Unit weight (kN/m^3)	Degree of saturation S_r (%)	Stress prior wetting (kPa)	*CP* (%) according to NAVFAC
TP-1	1	1.042	14.7	42	Natural w	–
	2	1.055	14.5	40	25	0.7
	3	1.077	14.5	42	100	5
	4	1.058	14.6	43	200	6.6
TP-2	1	0.887	16.9	60	200	3.8

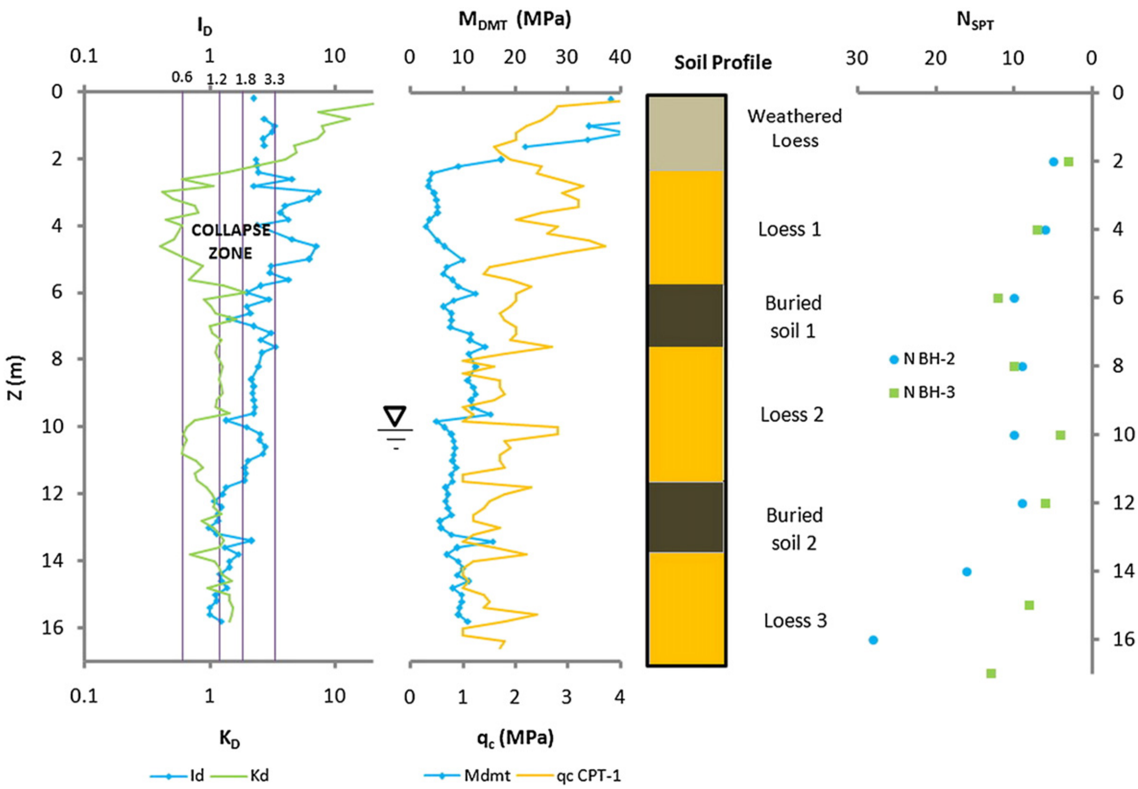

Fig. 5. DMT-1 results along with q_c from CPT-1 and N_{SPT} obtained in BH-2 and BH-3.

Similar values were also reported by Lutenegger and Donchev (1983), emphasising the importance that K_D may have for detecting collapse prone zones. In the first loess horizon values of I_D are in the sand ($I_D > 3.3$) and subordinately in the silty sand ($1.8 < I_D < 3.3$) region. The values I_D and K_D indicate that collapsing loess "behaves" more like a sand than a clay. The author believes that this behaviour may indicate potential collapse zones, or in other words, a particular numerical value of K_D and I_D will be able to better point to the problem of collapse than

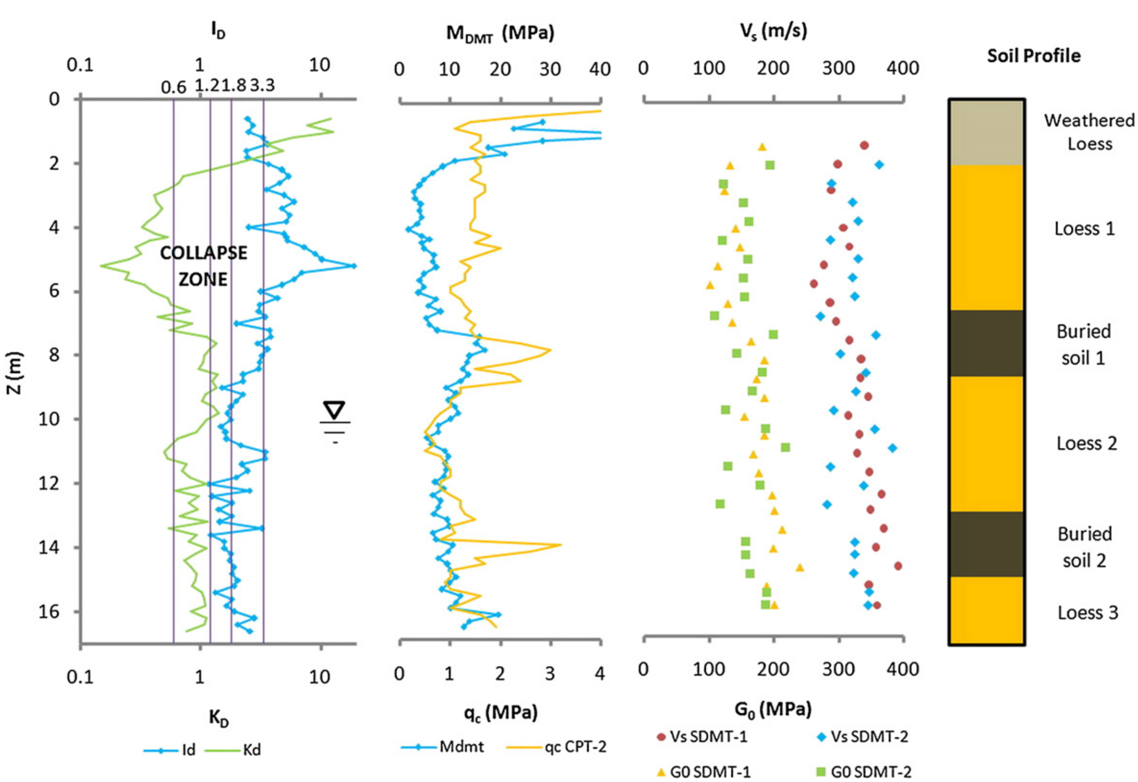

Fig. 6. SDMT-2 results along with q_c from CPT-2 and V_s measured by SDMT-1.

K_D itself. Simultaneous observation of the changes of I_D and K_D with depth on a semi-log graph in the same scale is recommended. In this way the relative distance between them may be clearly noticed and the larger the distance becomes, the greater the risk of collapse. Generally, in collapsing loess, K_D tends to be lower than 0.6 while I_D is higher than 3. When compared to other specific phenomena, such as liquefaction, it is seen that in collapsing loess K_D values are three times lower than that found in clean sand safe against liquefaction in non-seismic areas, e.g. $K_D > 1.7$ proposed by Monaco et al. (2005). It is possible that the reason why low values of K_D were obtained is the existence of low horizontal stresses in the soil, which is directly reflected by low K_D. Handy (1995) and Handy and Ferguson (1994) reported values of K_0 in collapsing loess as low as 0.1 measured by K_0-stepped blade. Pit excavation revealed the existence of voids with diameters that reach up to several centimetres, so it can be assumed that if the blade encounters one of these voids during penetration, the first reading A should be equal to ΔA (pressure necessary to overcome membrane stiffness), which complies with the conditions of membrane expansion in free air. However, A was always greater than ΔA, which rules out the possibility of pumping membrane in free air. Also, it was observed that the membrane did not return to its seating position (buzzer was off) after deflation, which usually occurs in dry sands according to author's experience. The extent and significance of the disturbance effect due to blade penetration in collapsing loess still needs to be investigated.

The second loess horizon is characterised by higher K_D and lower I_D values than in the first loess horizon. At the depth of 10 m, which corresponds to the level of groundwater, all penetration tests show sharp decline of measured values. Field identification tests performed on samples from boreholes have shown that the second loess horizon located below and above the water level is of similar grain size and plasticity and therefore it is very interesting to find differences between measured parameters within the same geological unit, above and below the aquifer. These differences can be attributed to changes in degree of saturation above and below aquifer and is most noticeable from the DMT results. When I_D and K_D are viewed simultaneously it may be observed that they are closer to each other when above the water level, while they are "distant" below the water level. The average value of K_D above the water level is 1.2, while below the water level it drops by 50% to 0.6. I_D seems to be less sensitive to the change in moisture than K_D. Similar results have been reported by Lutenegger (1988) for a series of tests conducted in partially saturated silts before and after saturation. Some erratic data in K_D and I_D profiles in the lower part of loess 2 and buried soil 2 can be attributed to carbonate concretions, the existence of which at this depth was confirmed from the boreholes logs. In buried soil K_D tends to increase, and I_D decreases due to higher clay content.

Unit weights of the first loess horizon estimated from DMT, according to the chart given in Marchetti et al. (2001), are about 15% higher than the values determined from block samples taken from TP-1, which can be regarded as representative of the first loess horizon. This is not surprising given that the chart is developed for "normal soils". If γ obtained from the laboratory is used to calculate preinsertion vertical effective stress and introduced in Eq. (3), K_D would increase but not significantly, while in this case M_{DMT} is insensitive to changes of K_D. In determining G_0, mistakes are possible when taking into account γ obtained from DMT and therefore caution is required.

8. Collapsing loess in relation to other soil types

Previously mentioned characteristic "behaviour" of I_D and K_D, is displayed on the log–log "collapsibility" chart, shown in Fig. 7. This chart considers all three DMT intermediate parameters, where the ratio I_D/K_D is applied to the vertical axis and E_D is normalized by the σ'_{v0} applied to the horizontal axis. The chart consists of areas outlined with boundaries of different values of I_D and K_D. In the chart, a horizontal line that intersects the vertical axis at the $I_D/K_D = 5$, represents the boundary that separates the data obtained in the first collapsing loess horizon from the data obtained in the second and third non-collapsing horizons. Due to soil inhomogeneity it is to be expected that some points from the first loess horizon lie below this boundary, but most importantly, the majority of them are above it. It is believed that the I_D/K_D ratio (in combination with E_D/σ'_{v0}) is useful for comparison of different soil types due to its large variability (three orders of magnitude). Besides, it is noted that for all three loess horizons E_D/σ'_{v0} is approximately less than 150. Also included are data related to other soil types (clay, silt

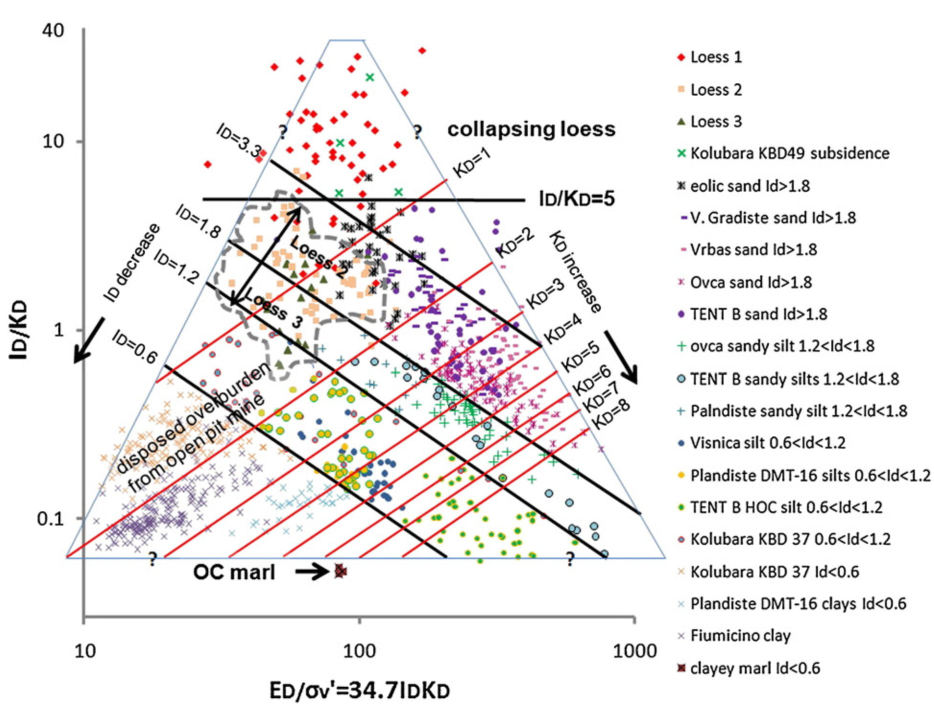

Fig. 7. Collapsibility chart.

Table 2
Details of the data indicated in Fig. 7.

Site/test name	Location	Description
Kolubara KBD49, subsidence	Kolubara open-pit coal mine	Low plasticity quaternary silty-clay with some gravel — overburden received from the mining operation disposed in the dump area by spreaders after coal extraction
Eolic sand $I_D > 1.8$	Veliko Gradiste (Kumane)	Silty sand with high carbonate content; wind blown; originating from Deliblato desert; deposited near source; $M_{DMT}/q_c = 4–5$
V. Gradiste sand $I_D > 1.8$	Veliko Gradiste	Medium dense NC sand; $M_{DMT}/q_c = 7$; $D_R = 35–65\%$
Vrbas sand $I_D > 1.8$	Vrbas town	Alluvial predominantly quartz sand; NC; $M_{DMT}/q_c = 6$; $D_R > 60\%$
Ovca sand $I_D > 1.8$	Belgrade	Alluvial predominantly quartz sand; NC; $M_{DMT}/q_c = 7$; $D_R > 60\%$
Tent B sand $I_D > 1.8$	Obrenovac	Alluvial sand with some gravel; NC; $D_R = 35–65\%$
Ovca sandy silt $1.2 < I_D < 1.8$	Belgrade	Silty sand; NC; interbedded with Ovca sand $M_{DMT}/q_c = 6$
Tent B sandy silt $1.2 < I_D < 1.8$ Tent B HOC silt $06 < I_D < 1.2$	Obrenovac	Flood plain sediments; upper part consists predominantly of sandy clay; desiccated; fissured — fissures filed with CH clay; the lower part is predominantly stiff CH clay rich with $CaCO_3$
Plandiste sandy silt $1.2 < I_D < 1.8$	Plandiste–Alibunar	Clayey to sandy silt; CL; 4–5% $CaCO_3$
Plandiste silt $0.6 < I_D < 1.2$	Plandiste–Alibunar	Clayey silt with lenses of fine sand; CL; 2–4% $CaCO_3$
Plandiste clay $0.6 < I_D$	Plandiste–Alibunar	Silty clay with 1–2% $CaCO_3$; CH
Visnica silt $0.6 < I_D < 1.2$	Belgrade	Marly clay; CL; stiff; fissured; major cementing material is carbonate and gypsum
Kolubara KBD-37 $0.6 < I_D < 1.2$ Kolubara KBD-37 $0.6 < I_D$	Kolubara open-pit coal mine	Soft to firm silty clay with coal fragments, organic; overburden produced from the mining operation, disposed by spreaders after coal have been extracted; $K_D < 2$ may indicate that volume changes due to self-weight is still ongoing.
Clayey marl $I_D < 0.6$	Obrenovac	Very stiff; MH-OH; DMT has been performed inside a borehole by statical push of the blade by drill rig.
Fiumicino clay	Italy	Data taken from SDMT software

*Average values of M_{DMT}/q_c are indicated where available. This ratio may indicate OCR in sand deposits (see Marchetti et al., 2001).
**Relative density (D_R) is estimated from chart proposed by Reyna and Chameau (1991) for NC uncemented sands.

and sand) obtained at different locations in Serbia in addition to Fiumicino clay from Italy, in order to perceive the position of loess in relation to them. The chart is accompanied by a legend which contains the locations and soil types introduced. Details on the data included in the chart are summarized in Table 2. From the chart it may be noted that loess and loess-like soils are indeed underconsolidated ($K_D < 2$), as indicated by Handy and Ferguson (1994). Within the collapsing loess zone there are points obtained by the testing of disposed material from open pits where subsidence has occurred. According to the author's experience, values of K_D less than 2 are more frequently encountered in sand than in clay, but obviously this depends on the geological history of specific locations. The lowest I_D/K_D ratio is obtained from clayey OC marl, but it can be even lower in more stiff soils. It would also be interesting to include in the graph other types of loess soils deposited in different environments in order to show their "position" relative to collapsing loess.

It should be emphasised that established criterion separate collapsing from non-collapsing loess for one particular location and that transition from low to high susceptibility to collapse cannot be defined with a single boundary. Susceptibility to collapse could be related to specific values of K_D and I_D, where lower K_D and higher I_D correspond to high susceptibility, while higher K_D and lower I_D correspond to low susceptibility to collapse. In order to prove this, more extensive research is needed so that K_D and I_D values can be linked to the degree of collapse, e.g. as defined by NAVFAC (1986). Nevertheless, this criterion is significant because it can indicate that:

- additional investigations are required for certain depth intervals,
- high mechanical disturbance of soil samples could be expected if conventional drilling methods are applied,
- specific types of laboratory tests are required to quantify *CP* for specified design conditions.

9. G_0/q_c relations for loess

It is now generally recognized that cemented soils tend to show higher V_s and small strain stiffness compared to uncemented soils. Based on theoretical considerations and experimental data Fernandez and Santamarina (2001) and Yun and Santamarina (2005) have shown that the behaviour of natural soils is greatly affected by cement content and confining pressure. They also identify two stress-regions: a low-stress region where behaviour is controlled by the cementation, and a high-stress region where the response is controlled by the state of stress. This is of particular importance for loess where the confining pressures are low and a cement controlled region prevails. On the other hand, suction is expected to have a similar impact as cementation on the small strain stiffness (Rinaldi and Santamarina, 2008). Eslaamizaad and Robertson (1996) and Schnaid (2005) showed that it is possible to identify cemented soils using the ratio G_0/q_c. This ratio is usually plotted against normalized dimensionless parameter q_{c1} defined as:

$$q_{c1} = (q_c/p_a)(p_a/\sigma\prime_v)^{0.5} \tag{10}$$

where: q_c is cone resistance, and p_a is atmospheric pressure.

The G_0/q_c ratio provides a measure of the ratio of elastic stiffness to ultimate strength and may therefore be expected to increase with ageing and cementation, primarily because the effect of these on G_0 is stronger than on q_c (Robertson, 2012; Schnaid, 2005; Viana da Fonseca et al., 2006). Fig. 8 shows the G_0/q_c ratio plotted against the normalized q_{c1} parameter for the three loess horizons. The points were obtained from the CPT-2 test and the adjacent SDMT-2 test, for which V_s was measured. Included in the figure are lower (LBC) and upper (UBC) bounds proposed by Schnaid (2005) for cemented soils. Results

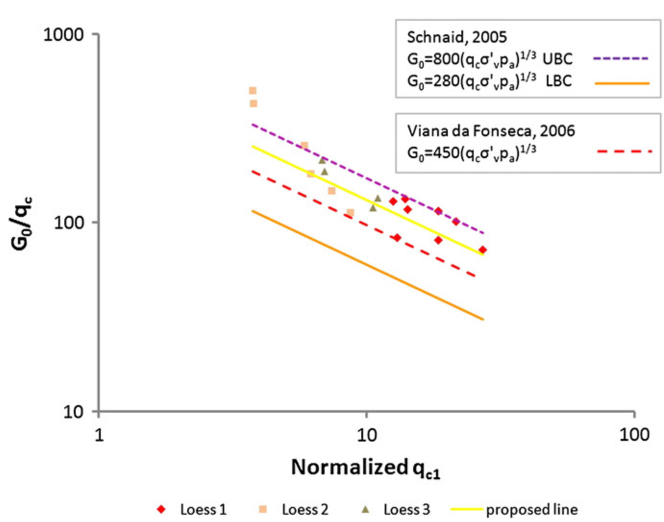

Fig. 8. G_0/q_c ratio vs. normalized q_{c1} parameter.

from residual-saprolitic soil from granite obtained by Viana da Fonseca et al. (2006) are also included. Almost all points for the three loess horizons plot between the upper bound for cemented soils proposed by Schnaid (2005) and the line proposed by Viana da Fonseca et al. (2006) for residual soil, which represents the lower boundary for this loess. Fig. 8 clearly indicates that loess is strongly structured lying near the upper bound for cemented soils. This is also evident for the second and the third loess horizons where principal cementing materials are the carbonates leached from the upper part of loess deposits, which have been observed from boreholes. It is interesting to notice that normalized q_{c1} values for collapsing loess are higher than q_{c1} values for the other two horizons due to higher q_c in collapsing loess. q_c can be considered as a measure of strength which is significantly increased by cementation and suction due to an increase in cohesion which is particularly significant in low confinement, as discussed by Rinaldi et al. (1998) and Eslaamizaad and Robertson (1996). Higher q_c values in collapsing loess can also be explained by results reported by Susic and Spasojevic (1995) who found, for the collapsing Belgrade loess, that q_c is strongly related to degree of saturation; q_c increases when degree of saturation decreases. In addition to these findings the influence of suction on q_c in predominantly quartz sand has recently been reported by Pournaghiazar et al. (2012). They found that the effect of suction on q_c is most significant for low confining stresses, which could also be assumed for loess where low confining stresses prevail. The opposite trend is evident from intermediate DMT parameters, where K_D is the lowest in collapsing loess with a tendency to increase in the other two loess horizons. This indicates that CPT and DMT behave very differently from each other in collapsing loess. This could be explained by the different operating modes of the two devices, as affected by loess anisotropy. K_D is obtained from p_0 (corrected A-reading) measured in the horizontal direction perpendicular to existing large vertical voids while q_c is measured parallel to these voids which cause reduction in horizontal stress. This stress reduction is reflected more to K_D than q_c.

The G_0/q_c ratio is lower in the first loess horizon than in the other two due to higher q_c values in the first loess horizon. For the preliminary design in loess with similar properties the following equation is proposed in order to evaluate G_0 from q_c

$$G_0 = 615(q_c \sigma\prime_v p_a)^{1/3}. \qquad (11)$$

This equation does not apply to buried soil and in the first loess horizon with preserved structure gives values that are closer to the lower bound, which are on the safe side. It should be emphasised that this expression is only an approximate indicator of G_0 and does not replace the need for in situ V_s measurements. In the previous discussion G_0 and q_{c1} have been derived with 15% reduced unit weights obtained from DMT as explained in Section 7. The comparison of vertical profiles of q_c (CPT-2) and M_{DMT} (SDMT-2) shown in Fig. 6 reveals that the M_{DMT}/q_c ratio for the first loess horizon is 3.5 while in the second and third horizons this ratio tends to increase to an average value of 10. According to Marchetti et al. (2001) and Monaco et al. (2014) M_{DMT}/q_c ratio can be used to estimate OCR in sands where M_{DMT}/q_c increases with OCR (also with K_D). Devincenzi and Canicio (2001) reported values of M_{DMT}/q_c in loess-like deposits ($e_0 = 0.62$; $\gamma_d = 16$ kN/m^3, $K_D = 8$) before and after saturation of 20 and 9 respectively. The general trend is that this ratio increases when K_D increases, which is also the case in examined loess. The usefulness of this ratio in loess still needs to be investigated, nevertheless, it can be seen that in the loess with preserved structure the ratio is much smaller than in collapsed loess.

10. Extension of G_0/M_{DMT} diagrams

The data in Fig. 6 indicates high V_s compared to low K_D values. It seems that the measured V_s is not a “proper match” for low K_D and M_{DMT} values. This can be explained by the cementation developed in loess that is preserved at small strains induced by shear wave, against medium to high strains induced by blade penetration resulting in low K_D and M_{DMT}. This was also noticed by Monaco and Marchetti (2007) in volcanic sands in Cassino, Italy.

Marchetti et al. (2008) and Monaco et al. (2009) presented diagrams of the ratio G_0/M_{DMT} plotted as a function of K_D in order to facilitate determination of G_0 from I_D, K_D and M_{DMT}. The diagrams have been grouped according to soil type ($I_D < 0.6$ for clays, $0.6 < I_D < 1.8$ for silts and $I_D > 1.8$ for sands), where for each group best fit equations were established in the form of a power function as:

$$G_0/M_{DMT} = aK_D{}^{-b} \qquad (12)$$

where a and b are constants which differ depending on the soil type. G_0/M_{DMT} ratios and constants a and b taken from Marchetti et al. (2008) are given in Table 3 for the three soil types. Cruz et al. (2012) recognized that the G_0/M_{DMT} ratio can be used to distinguish between residual (cemented) and de-structured sedimentary soils for the same range of I_D. Constants a and b from Cruz et al. (2012) also are included in Table 3, but it should be emphasised that the Cruz et al. (2012) equation has been proposed for $I_D > 1.2$ thus it should be valid for sand represented with $I_D > 1.8$. For the three loess horizons the best fit equation is represented in the form of a power function where $a = 17.58$ and $b = -0.57$, as shown in Table 3.

It can be seen that exponent b for loess is very different than for normal soils and is closest to exponent b for residual soils, while constant a is similar to that of silts. These trends indicate that loess is essentially silty soil with unusual behaviour. From Table 3 it emerges that G_0/M_{DMT} ratios for loess are much higher than those of sands, both represented with $I_D > 1.8$, and even higher than those of clays where the widest range in the G_0/M_{DMT} ratio is observed (Marchetti et al., 2008). General trends for normal soils show an increase in G_0/M_{DMT} ratio as I_D decreases, while for loess the opposite is true, i.e. for the first loess horizon where I_D is higher compared to the other two loess horizons the G_0/M_{DMT} ratio is also higher. This behaviour is also unusual and could be used as an indicator of collapsing loess but more data are needed to draw a more precise conclusion.

Graphical representation of the G_0/M_{DMT} ratio for the three loess horizons ($I_D > 1.8$) plotted as a function of K_D is given in Fig. 9 in arithmetic scale and in Fig. 10 in bi-logarithmic scale. In these figures the best fit equation for sands ($I_D > 1.8$) proposed by Marchetti et al. (2008) and the upper sedimentary/lower residual bound ($I_D > 1.2$) proposed by Cruz et al. (2012) are included. From the figures it can be observed that G_0/M_{DMT} decreases as K_D increases which is common for all soils. For the first loess horizon, where K_D is less than 0.6, the widest range and maximum variability of G_0/M_{DMT} is found. For the first loess horizon G_0/M_{DMT} is mostly in the range 21 to 50, while in the second and third

Table 3
Parameters a and b for use in Eq. (12) for various soil types.

Soil type	G_0/M_{DMT}	a	b	Coef. of determination (R^2)	Reference
Clay ($I_D < 0.6$)	1–20	26.177	−1.0066	0.61	Marchetti et al. (2008)
Silt ($0.6 < I_D < 1.8$)	1–10	15.686	−0.921	0.81	
Sand ($I_D > 1.8$)	0.5–3	4.5613	−0.7967	0.65	
Sandy silts, sands ($I_D > 1.2$)	/	6.5	−0.691	/	Cruz et al. (2012)
Loess ($I_D > 1.8$)	10–50	17.58	−0.577	0.644	This study

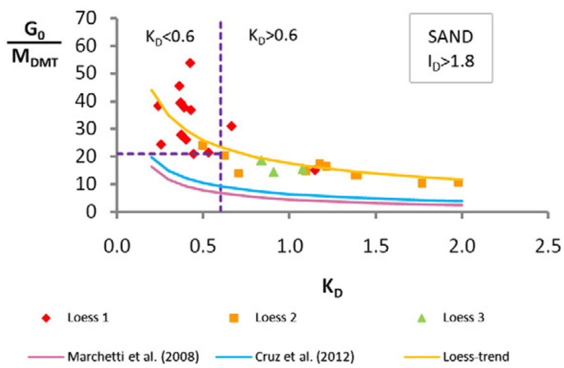

Fig. 9. Ratio G_0/M_{DMT} vs. K_D for loess (arithmetic scale).

horizons it is less than 21. Thus it seems that collapsing loess is distinguished by $G_0/M_{DMT} > 21$, and $K_D < 0.6$ as shown in Fig. 9. The major influence on G_0/M_{DMT} has M_{DMT}, which tends to increase more rapidly over depth than G_0. Fig. 10 indicates that points representing loess plot above lines proposed by Marchetti et al. (2008) and Cruz et al. (2012), and the trend line for loess have a lower slope than the other two for $I_D > 1.8$.

11. Module comparison

Fig. 11 shows the vertical profile of the M_{DMT} in the first loess horizon, cumulative for all three DMT tests, in addition to E_{oed} values obtained from the block samples taken from pit TP-1. Obviously, these results correspond well, indicating that the Marchetti (1980) correlation can be used in collapsing loess to obtain constrained modulus at natural moisture content. This was demonstrated on a limited number of results obtained at the same depth, yet it may be noted that the M_{DMT} value is in an intermediate position between results obtained on the three samples collected from the pit. It would be preferable to obtain a larger number of laboratory data for various depths in order to support this "single depth comparison". It should be noted that K_D has no significant influence on the correction factor R_M used for obtaining M_{DMT}. The reason for this lies in the fact that R_M is always 0.85 when K_D is lower than 1.5. Thus M_{DMT} is obtained by reducing E_D to 85% of its initial value. Fig. 7 indicates that the value of E_D in the first loess horizon can be expressed as a linear function of vertical effective stress such as $45\sigma'_{v0} < E_D < 150\sigma'_{v0}$, where for increasing values of σ'_{v0} the ratio of E_D/σ'_{v0} decreases. At the present there is no possibility of estimating constrained modulus in a fully saturated state from DMT. This would be possible if M_{DMT} values were determined before and after saturation.

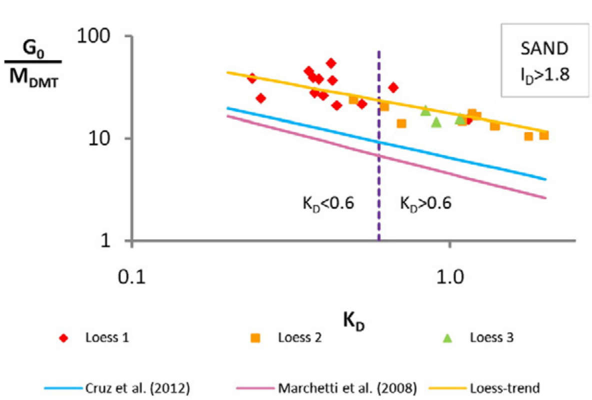

Fig. 10. Ratio G_0/M_{DMT} vs. K_D for loess (log–log scale).

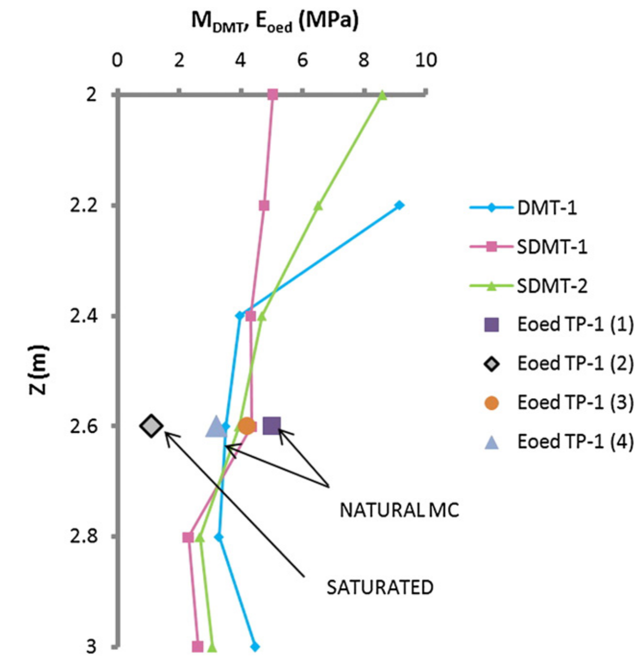

Fig. 11. Comparison between M_{DMT} obtained from DMT and E_{oed} determined from block samples.

12. Conclusions

The results presented in this paper indicate the following:

1. Single oedometer tests indicate that the first loess horizon is prone to collapse after saturation, with *CP* according to NAVFAC (1986), of 6.6%. The second and the third loess horizons are changed under the influence of wetting and overburden weight.
2. The values of the dry unit weight obtained from borehole samples are 20% higher than the values obtained from block samples. This is caused by mechanical disturbance of the loess structure which causes compression during sampling. Unit weights of the first loess horizon estimated from DMT are about 15% higher than the values determined from block samples.
3. I_D and K_D combined may indicate potentially collapsing loess zones. It is recommended that the vertical profiles I_D and K_D are simultaneously observed in the semi-log scale in order to more reliably isolate collapsing zones, which are characterised by a rapid decrease in K_D and a rapid increase in I_D. The farther they are from each other, the greater the potential for collapse. The first loess horizon is represented with $K_D < 0.6$ and $I_D > 3$.
4. For the Zemun loess plateau it was established that if the I_D/K_D ratio is greater than 5, loess is prone to collapse. The I_D/K_D ratio (in combination with E_D/σ'_{v0}) is useful for comparison with other soil types when a large quantity of data is presented due to its large variability (three orders of magnitude).
5. Collapsing loess is characterised by the ratio $G_0/M_{DMT} > 21$ for $K_D < 0.6$. G_0/M_{DMT} in loess is higher compared to other soil types presented in the literature.
6. The G_0/q_c ratio indicates that loess is a highly structured soil with a lower G_0/q_c ratio in the first loess horizon compared to the other two due to higher q_c values.
7. The correction factor R_M is 0.85, due to low K_D values that are less than 1.5. M_{DMT} determined from the correlation proposed by Marchetti (1980) agrees well with the value of the oedometer modulus determined on undisturbed samples at natural moisture content collected from the test pit. The constrained modulus E_{oed} can be simply evaluated as $0.85E_D$. If collapse of the soil structure is to be expected, based on I_D and K_D, the amount of settlement after saturation

should be evaluated from modulus obtained by testing a soil that is previously wetted. In order to achieve this, DMT should be performed after wetting the soil in situ. This is recommended for future research.

All results shown here are dependent on local site conditions, but in order to establish more general trends, additional comparative DMT and laboratory tests are needed.

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